

Limits in Optics – How to Bargain with Nature

Gerd Häusler*, Christian Faber**, Pavel Pavlicek***

* Institut für Optik, Information und Photonik, Friedrich-Alexander-Universität Erlangen-Nürnberg

** Fakultät Elektrotechnik und Wirtschaftsingenieurwesen, Hochschule Landshut

*** Joint Laboratory of Optics, Olomouc, CZ

gerd.haeusler@fau.de

In a 2006 letter to the DGaO community, Adolf Lohmann revealed that his major source of inspiration was linear systems theory. We follow his recommendation and introduce a systems theory of optical metrology, leading to a large “invention matrix”. We categorize the plethora of sensor options by their limits.

1 Introduction

This article is dedicated to our teacher Adolf Lohmann (“AL”). After his 80th birthday celebration by the DGaO in 2006, AL sent a letter to the community to express his gratitude. On eight handwritten pages [1], as a present to the DGaO, he revealed that systems theory was the primary source of his inspiration and he encouraged the optical community to follow this line. We take up this suggestion and present a purposeful systems theory of optical metrology.

2 Why systems theory in optical metrology?

Systems theory teaches that the signal from the source has to be properly encoded for error-free and efficient transmission before (electronic) noise is added in the channel, see Fig. 1. Considering an optical measuring system as a communication system [2], it turns out that the major role of optics is not that much “imaging”; it is “source encoding”:

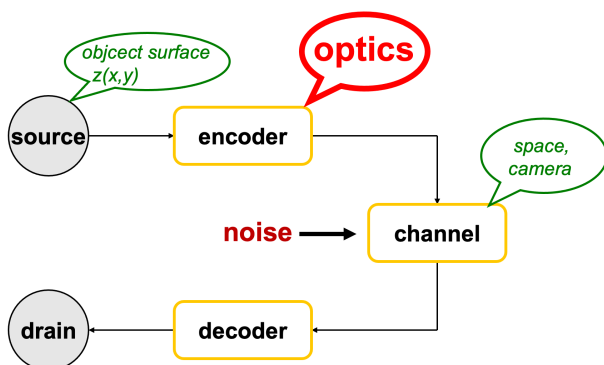


Fig. 1 Optical sensor as a communication system

For this purpose, optics provides a large toolbox, as illustrated in Fig. 2. Just a small selection of tools: **Illumination** can be coherent or incoherent, directed, diffuse, structured, mono- or polychromatic, static or dynamic. **Light-matter interaction** with the object can be diffuse or specular, at the surface or in the volume, coherent or incoherent, linear or non-linear. The **observed modality** may be the complex amplitude or the intensity, the number of photons,

the polarization, the coherence, the time of flight, just to name a few. The competition for novel options is open, specifically in view of quantum optics.

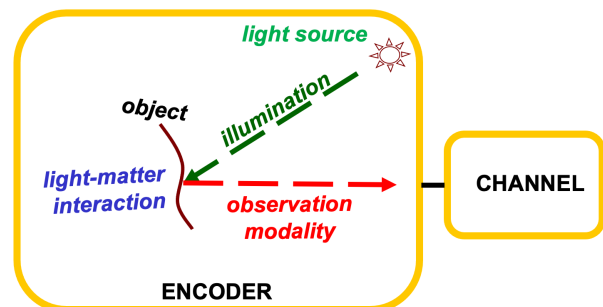


Fig. 2 The major role of optics is “source encoding”, via illumination, light-matter interaction, and the proper choice of the observation modality

This systems-theoretical view on optical sensors offers a large *configuration space* for sensor solutions, illustrated in Fig. 3.

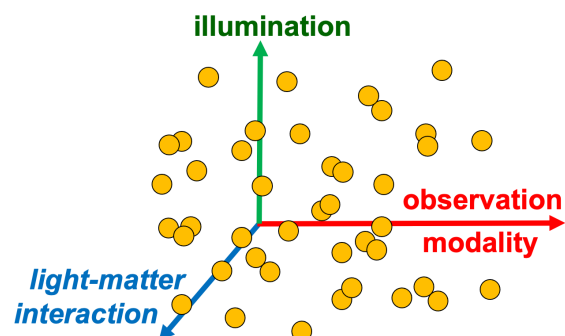


Fig. 3 3D-configuration space for thousands of sensor options

By combining the features, thousands of sensor options can be created. We emphasize that this is not just a gimmick; we may interpret Figure 3 as a large three-dimensional invention matrix, in the sense of Adolf Lohmann [3], see Fig. 4.



Fig. 4 Adolf Lohmann's self-explaining walking-stick invention matrix. Picture taken from ref. [3]

3 About limits and encoding

We can bring order to the plethora of sensors from Fig. 3 by searching for their limits. We will also sketch the major ingredients of encoding. The sensor options can be categorized, first according to the dominant physical source of noise, and second according to how this noise depends on the observation aperture. Four types of 3D-sensors can be distinguished. For details and more references, see [4], and on <http://tinyurl.com/haeuslerweb>.

Triangulation (type I sensor): The measurement uncertainty on rough surfaces is strongly limited by speckle noise and by a small observation aperture. It is important that speckle "noise" is a systematic error that cannot be calibrated. For better encoding, we can reduce speckle "noise" to a certain extent via spatially less coherent illumination or perfectly by creating fluorescent light-matter interaction.

The measurement uncertainty of **rough-surface coherence scanning interferometry (type II)** is just the surface roughness (a few μm), not depending on the observation aperture. This is a remarkable feature, as we can measure within deep bore-holes and from large distances. The encoding is via illumination with low temporal coherence and high spatial coherence. The latter is necessary to generate speckles as the carrier of local interference.

Classical (smooth-surface-) interferometry (type III sensor) is limited by photon noise, enabling a virtually unlimited precision. However, smooth-surface interferometry averages the profile over the area of the diffraction spot, resulting in a local profile error depending on the inverse of the observation aperture. There is more "smoothing" for a smaller observation aperture, as shown in Fig. 4.

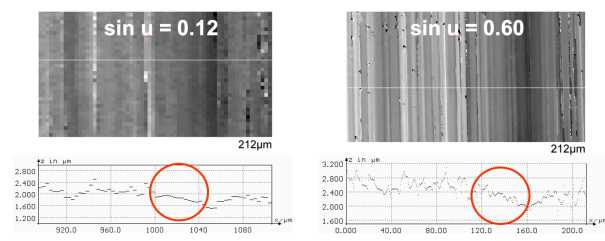


Fig. 5 Classical interferometry averages the local profile over the diffraction spot, smoothing the results depending on the observation aperture

The surface profile is encoded via the local phase of the reflected wave. It will be decoded from the

intensity interference pattern after (!) the channel.

The measuring uncertainty δz of **deflectometry (type IV)** comes as an extremely useful uncertainty product: $\delta z = \delta x \cdot \delta \alpha \sim \lambda / \text{SNR}$, connecting the lateral resolution δx (aperture-dependent) and the angular measuring uncertainty $\delta \alpha$. Even with low-cost hardware (SNR~1000), we can achieve a depth uncertainty δz of 1 nm. And we can bargain with nature for either micro-arcsec angular resolution with very low aperture, or microscopic lateral resolution.

The encoding for deflectometry is extremely efficient: The inherent signal is the local slope. Local profile variations are precisely measured, while redundancy is strongly reduced. Illumination is virtually incoherent, leading to photon noise limitation.

Can we find more limits? For **self-luminous objects** such as **stars** or **fluorescent molecules**, the lateral localization uncertainty is limited by photon noise, as in classical interferometry, and goes with the inverse of the central curvature of the measured spot signal. With many photons, nanometer-precision is possible, as exploited in astronomy and in modern F-technique microscopy.

A very similar result holds for the lateral localization of a **digital 3D-model in 3D space**. Such a localization is important for the so-called 'registration' of 3D-data, taken from different directions [5].

An important **statistical limit** is the Cramér-Rao lower bound, which allows calculation of the lowest possible measurement uncertainty from the analytical expression of the signal and the probability density function of the noise. In [6], the measurement uncertainty of the sensors mentioned above is derived in a tutorial way, via the Cramér-Rao bound.

4 Conclusions

We followed Adolf Lohmann's recommendation to apply systems theory to gain a new perspective on optical metrology, leading to a 3D generalization of his "invention matrix". This matrix represents a big toolbox to solve measuring problems by proper encoding.

5 References

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